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# TURBULENT SHEAR STRESS MEASUREMENT IN HYPERSONIC FLOW

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The present report refers to the experimental evaluation of additional shear stress terms which might be significant at high Mach numbers. These terms are necessary to develop accurate empirical turbulence models to be used in Navier-Stokes computational codes.

The measurement technique used was the simultaneous employment of hot wire anemometers in conjunction with laser doppler velocimeters to obtain density-velocity triple correlation terms and compressible shear stress distribution at Mach 6. This diagnostic tool is available for measurements of turbulent hypersonic flows. Comparisons of present laser velocimeter turbulence measurements with previous hot wire results indicate that significant errors can be incurred in hypersonic flows with the old standard techniques. Results indicate that adequate particle tracking is possible at Mach 6.

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# Turbulent Shear Stress Measurement in Hypersonic Flow

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Although extensive progress has been made in computational fluid mechanics, reliable flight vehicle designs and modifications still cannot be made without recourse to extensive wind tunnel testing. Future progress in the computation of hypersonic flow fields is restricted by the need for a reliable turbulence modeling data base which could be used for the development of empirical models for use in Navier-Stokes codes. Currently, there are few compressible flow measurements which could be used for this purpose and, since additional shear stress terms may be significant at high Mach numbers, models based on incompressible measurements may not be realistic. An evaluation of these additional terms will require new experimental approaches.

## 1. Introduction

Current hypersonic flow field instrumentation is insufficient to meet current and future ground test requirements. Measurements are required to establish the basic physical mechanisms and turbulence models required for reliable prediction of transitional and turbulent hypersonic flow fields.

At present, the principal research tools for turbulence measurement in low speed flows are hot wire and laser anemometers. In hypersonic flows, hot wires can be used reliably to measure mass flux and total temperature fluctuations but cannot be used in flows which involve high levels of turbulence, separation or time-dependent flow reversal which are often associated with shock/boundary layer interactions. On the other hand, due to resolution limitations, the laser anemometer is not suitable for low turbulence, freestream measurements. But, with its linear and directional sensitivity, it probably represents the instrument of last resort for the non-intrusive measurement of large scale, unsteady turbulent hypersonic flows.

A hot wire anemometer senses any changes in the variables which affect the rate of heat-transfer between the wire and the fluid. Variations in heat transfer coefficient can change both wire temperature and resistance. If the wire is made part of a suitable electrical circuit, these changes can be used to generate a signal which is related to the instantaneous heat transfer. Unfortunately, our knowledge in each of these categories is far from complete and could well be responsible for the current lack of reliable data. A recent review (Ref. 1) of supersonic and hypersonic hot-wire data taken in zero pressure gradient, adiabatic or isothermal wall boundary layers illustrates the problem. Fig. 1 shows data from several sources for the fluctuating axial velocity component. The scatter is so large that it is impossible to construe that any form of similarity with Reynolds or Mach number exists. The picture is even more confusing when the distributions of the other two normal stresses are reviewed. The measured shear stress distributions (Fig. 2) once again show that no pattern of similarity can be observed. Indeed, only Klebanoff's incompressible measurements (shown for comparison) approach the anticipated limiting value of unity in the wall region. These results give some indication of the deficiencies in the measurement techniques and data reduction assumptions.

Principal sources of hot wire turbulence measurement uncertainty are the assumptions involved in reducing the hot wire measurements of mass flux and total temperature fluctuations to terms which appear directly in the momentum and energy equations. For example, to obtain the axial velocity fluctuation levels, we assume that the flow field is isentropic. This permits us to write the energy equation in its differential form as

$$\frac{1}{\alpha}\frac{\partial T_t}{T_t} = (\gamma - 1)M^2\frac{\partial u}{u} + \frac{\partial p}{p} - \frac{\partial \rho}{\rho} \qquad 1$$

$$\text{where} \quad \alpha = 1/(1 + \frac{\gamma - 1}{2}M^2)$$

Then we consider the equation for the mass flow per unit area and time in its differential form

$$\frac{\partial m}{m} = \frac{\partial u}{u} + \frac{\partial \rho}{\rho} \qquad 2$$

Substituting for $\partial\rho/\rho$ in equation 1 gives

$$\frac{1}{\alpha}\frac{\partial T_t}{T_t} = (\gamma - 1)M^2\frac{\partial u}{u} + \frac{\partial p}{p} - \frac{\partial m}{m} + \frac{\partial u}{u} \qquad 3$$

or, collecting terms, we obtain

$$\frac{\partial u}{u} = \frac{1}{\alpha[1 + (\gamma - 1)M^2]}\frac{\partial T_t}{T_t} - \frac{1}{[1 + (\gamma - 1)M^2]}\left[\frac{\partial p}{p} - \frac{\partial m}{m}\right] \qquad 4$$

which, defining $\beta = \alpha(\gamma - 1)M^2$, can be written as

$$\frac{\partial u}{u} = \left(\frac{1}{\alpha + \beta}\right)\frac{\partial T_t}{T_t} - \left(\frac{\alpha}{\alpha + \beta}\right)\left[\frac{\partial p}{p} - \frac{\partial m}{m}\right] \qquad 5$$

In past shear layer studies, the effect of pressure fluctuations has been negelected so that, with $p'/p << 1.0$, equation 5 may be written as

$$\frac{u'}{\bar{u}} = \left(\frac{1}{\alpha + \beta}\right)\frac{T_t'}{\bar{T}_t} + \left(\frac{\alpha}{\alpha + \beta}\right)\frac{(\rho u)'}{(\overline{\rho u})} \qquad 6$$

Squaring both sides of this equation leads to an expression for the streamwise turbulence intensity in the form

$$\frac{\overline{u'^2}}{\bar{u}^2} = \left(\frac{1}{\alpha + \beta}\right)^2 \frac{\overline{T_t'^2}}{\bar{T}_t^2} + \frac{2\alpha}{(\alpha + \beta)^2}\frac{\overline{(\rho u)' T_t'}}{(\overline{\rho u}\,\bar{T}_t)} + \left(\frac{\alpha}{\alpha + \beta}\right)^2 \frac{\overline{(\rho u)'^2}}{(\overline{\rho u})^2} \qquad 7$$

Clearly the measurement accuracy is governed by a pressure fluctuation assumption which is probably not valid in hypersonic flows, and questionable, low-overheat determinations of the first two terms in equation 7. The procedures used to evaluate other terms which appear in the momentum and energy equations are reviewed in Ref. 2. These analyses show that previous hypersonic hot wire measurements could be subject to substantial errors.

The problem is further compounded by the fact that, at high Mach numbers, other turbulent stress terms may well be important and the shear stress may not be adequately represented by the incompressible term alone. Integration of mean flow data obtained in hypersonic shear flows (ref. 3) shows that the compressible shear stress distribution is given by

$$\overline{(\rho v)'u'} = \bar{\rho}\,\overline{u'v'} + \bar{v}\,\overline{\rho' u'} + \overline{\rho' u' v'}. \qquad 8$$

Generally, the last two terms on the right-hand side are considered to be negligible. However, since density fluctuation levels scale with the square of the local Mach number and significant flow field angularity can be induced in shock-boundary layer interactions, the latter two terms could become important in high speed interacting compressible flows.

The measurement of these additional terms will require new experimental approaches.. The purpose of this report is to describe a technique which combines the advantages of both hot wire and laser velocimeter measurement techniques to determine all three shear stress terms in a variety of hypersonic flows.

## 2. Experimental Details

The method proposed for the on-line determination of the instantaneous values of $\rho$, u, v and the subsequent calculation of their mean and RMS values and the three shear stress terms is shown schematically in Fig. 3. It combines the output of a two component laser doppler velocimeter with a single hot wire normal to the flow. The continuous output from the hot wire is fed directly into an analog to digital converter to provide 12 bits of digital information at 50 kHz. This is more than sufficient to provide essentially real time point mass flow data in digital form. But, data from the two component laser velocimeter system are not necessarily continuous wave since particle arrival times in the focal volume are random and data rates are generally low in high speed facilities. However, whenever valid and essentially coincident data are received on both channels, they are recorded along with the corresponding digitized hot wire voltage for subsequent analysis.

The hot wire anemometer and laser velocimeter measurements were made in the AFWAL M=6 High Reynolds Number Wind Tunnel, which is an open jet, blow down facility. It was designed to produce a maximum free stream unit Reynolds number of $3\times10^7$ per foot and operates over a stagnation pressure range from 700 to 2100 psia at a fixed stagnation temperature of 1100 R. The supply air is heated in a pebble bed storage heater which allows run times of up to 100 seconds at the maximum mass flow rate of 90 pounds per second. The present measurements were obtained in zero pressure gradient flat plate flows over smooth and rough surfaces.

Before each blow down run, a single normal hot wire was positioned in the boundary layer at a fixed, known distance from the wall and the focal volume of the two component velocimeter was positioned at the same vertical location but slightly ahead of the wire. The 5 μm Pt-Rh constant temperature hot wire was operated at high overheat to ensure its response to local mass flux fluctuations. At each fixed location, several thousand individual velocimeter and hot wire realizations was recorded. This was followed by a hot wire boundary layer traverse for calibration purposes. Each calibration was used to determine the instantaneous mass flux for each pair of velocimeter realizations during the run. Hardware was designed and software was written to provide for the subsequent determination of the three variables and shear stresses as shown schematically in Fig. 4. A data acquisition system was developed which enabled two component laser velocimeter measurements along with hot wire data to be processed, stored and plotted on-line. The test results were then used to evaluate the relative importance of the three shear stress terms.

## 3. Test Results

The hot wire can be used to reliably measure the local mass flux fluctuations at high over heat ratios. However, the combined instrumentation cannot be used with confidence to determine instantaneous density and velocity until the ability of the laser velocimeter seed particles to follow the flow at hypersonic speeds has been confirmed. To address this problem, mean and fluctuating axial velocity profiles were measured at several axial stations in the zero pressure gradient, smooth flat plate flow.

Measurements obtained for a momentum thickness Reynolds number of 8000 are shown in Fig. 5, which shows the results of the law-of-the-wall transformation when the data are compared with the incompressible correlation of Coles (Ref. 4). This transformation, made using a wall friction velocity based on the calculated local skin friction, confirms the validity of the mean velocity measurements. In the law-of-the-wall, the data have the correct incompressible slope and show a wake-like region near the outer edge of the boundary layer similar to the incompressible observations. The same data have also been transformed to velocity-defect variables in Fig. 6. The agreement in the outer portion of the boundary-layer is consistent with the wake-like behavior displayed in law-of-the-wall variables. Once again, there is good agreement with the incompressible correlation.

The results of a more stringent test of the laser velocimeter measurements are shown in Fig. 7 where the zero pressure gradient turbulence measurements are compared with Klebanoff's incompressible results. There is good agreement between the hypersonic laser velocimeter and incompressible hot wire data when normalized by the wall friction velocity. This is in contrast to previous hot wire compressible flow results, reviewed in Ref. 5, which show a monotonic decrease with increasing Mach number. However, all these past hot wire results have been evaluated assuming zero pressure fluctuations which we would expect to become more important with increasing Mach number. It can be seen from equation 7 that this assumption could have a significant influence on the calculated hot wire velocity fluctuations at high Mach numbers. Turbulence measurements across the rough flat plate boundary layer are also shown in Fig. 7. As expected, there is a significant increase in the fluctuation level across the layer especially close to the wall. These increases are probably due to shocklets created by the roughness elements. These test results along with additional data reported in Ref. 6 indicate that adequate particle tracking and reliable laser velocimeter measurements can be obtained in the M=6 facility.

With this capability, hot wire and laser velocimeter measurements have been made across the zero pressure gradient, rough flat plate boundary layer. The mean and RMS density fluctuations were obtained from the instantaneous hot wire and laser velocimeter axial velocity measurements and are shown in

Figs 8 and 9. It can be seen that the computed mean density values are in good agreement with the profile calculated using conventional pitot pressure and total temperature measurements. The maximum density fluctuation levels are about 15 per cent close to the wall. As expected, these values are somewhat higher than data inferred from hot wire and laser induced fluorescence measurements in smooth wall, zero pressure gradient boundary layers at similar freestream Mach numbers.

The velocity and density cross correlations are shown in Figs. 10-12. Fig. 10 shows the variation of the turbulent velocity correlation coefficient across the boundary layer. The maximum value of approximately -0.4 is in close agreement with incompressible shear layer observations. The distributions of the velocity-density cross correlation and the velocity-density triple correlation coefficients are shown in Figs. 11 and 12. As expected, the $\overline{\rho'u'}$ and $\overline{\rho'u'v'}$ terms are positive as turbulent mixing will produce eddies with either higher velocities and density originating from the outer layers or low velocity and density fluid from the wall region.

The compressible shear stress distributions are shown in Fig. 13 where it can be seen that, at this Mach number, the contribution of the additional compressible terms is not significant. However, although these additional terms are small, they do follow consistent trends which once again confirms the validity of the experimental approach.

Although, in this test case, the additional terms which appear in the compressible shear stress formulation are small, the data show that the term $\overline{\rho'u'}$ is in fact significantly greater than $\overline{u'v'}$. Thus, in flows where the mean vertical velocity is of comparable magnitude to the local mean axial velocity, the compressible term $\bar{v}\overline{\rho'u'}$ could well be significant. Also, as density fluctuations generally scale with the square of the local Mach number, the triple correlation term could also be significant in higher Mach number flows. Clearly then, from a turbulence modeling viewpoint, both compressible shear stress terms could be important in the numerical modeling of hypersonic flows involving mean flow curvature and/or shock-boundary layer interactions.

## 4. Concluding Remarks

Diagnostic tools are available to attempt the measurement of turbulent hypersonic flows, an area where comprehensive studies are lacking. However, measurement techniques must be used with understanding and care in appropriate test situations. Comparisons of the present laser velocimeter turbulence measurements with previous hot wire results indicates that past data reduction assumptions can result in significant measurement errors in hypersonic flows. Extensive work is needed to establish a reliable data base for turbulence modeling and to define the reliable ranges of hot wire and laser anemometer application.

The laser velocimeter mean flow and turbulence measurements were in good agreement with incompressible results. Although these results indicate that adequate particle tracking is possible in the M=6 facility, considerable work is still required to optimize seed particle requirements and to define the flow regions in which reliable particle tracking can be expected in other hypersonic test facilities.

The work will be extended to higher Mach numbers where the compressible shear stress terms should have additional significance. A variety of test configurations will be tested in the 20 in. Hypersonic Wind Tunnel. These tests will be designed to generate a reliable turbulence modeling data base for hypersonic flows.

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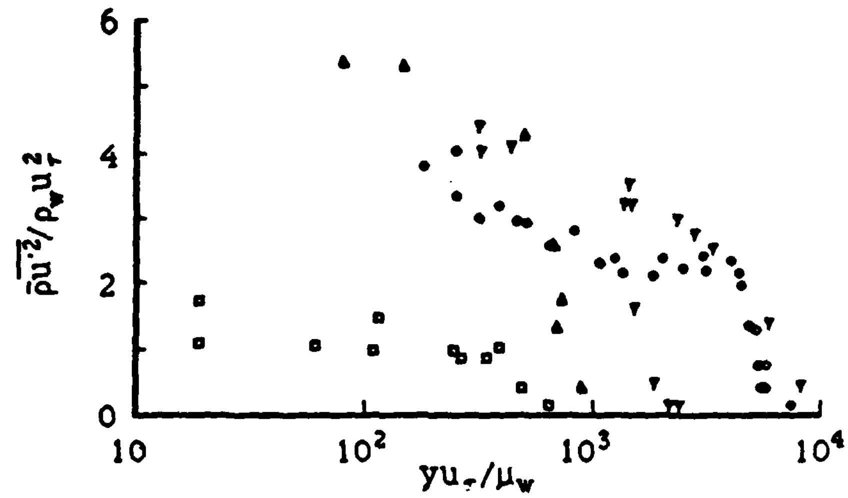


Fig. 1 Reynolds normal stress distribution in compressible turbulent boundary layers (ref. 1).

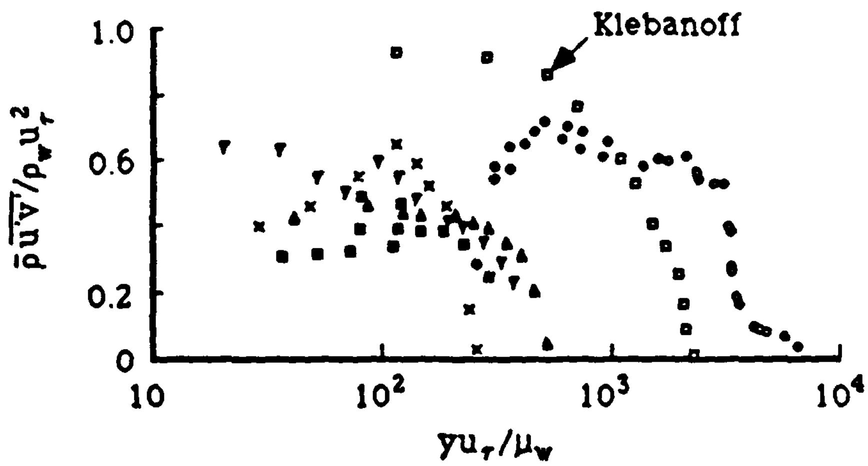


Fig. 2 Reynolds shear stress distribution in compressible turbulent boundary layers (ref. 1).

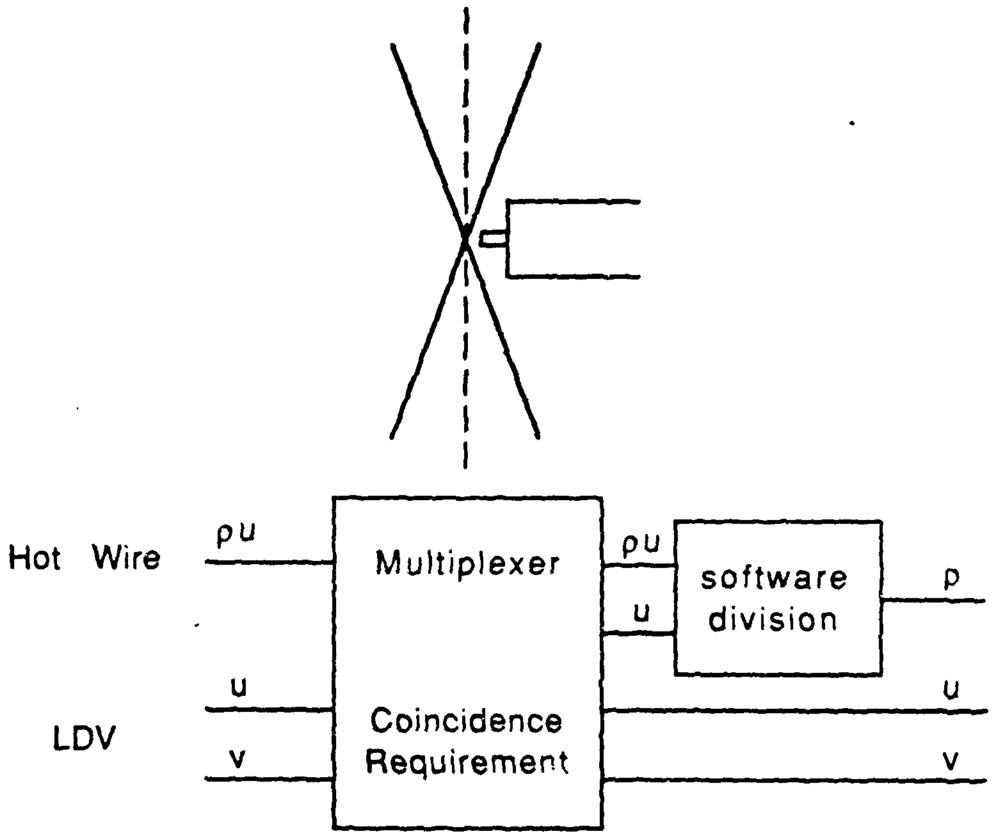


Fig. 3 Simultaneous Hot Wire - LDV Measurements

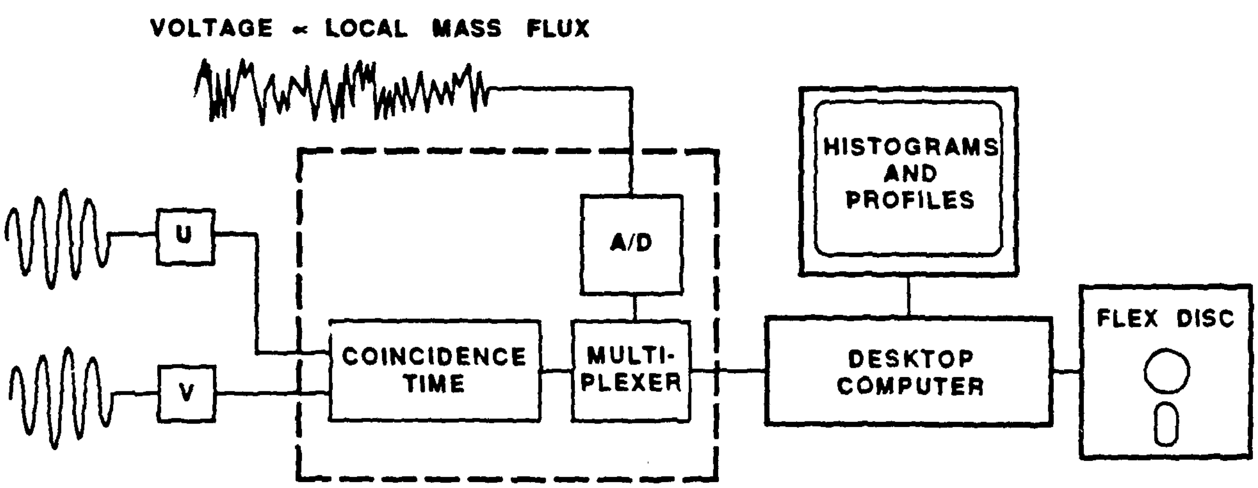


Fig. 4 Data Acquisition System

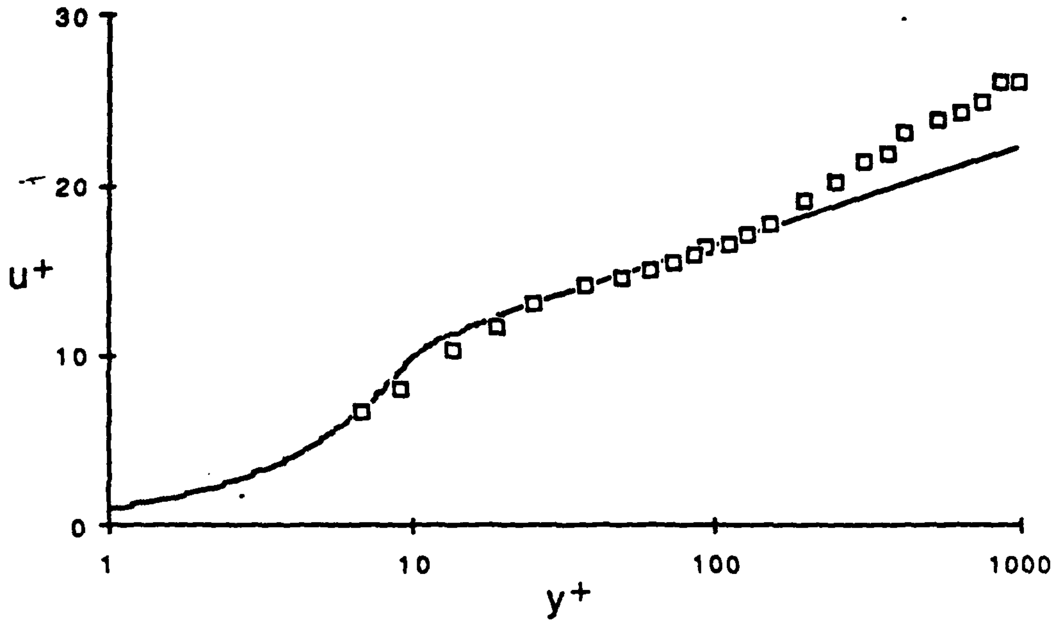


Fig. 5 Law-of-the-wall Correlation in Incompressible Coordinates.

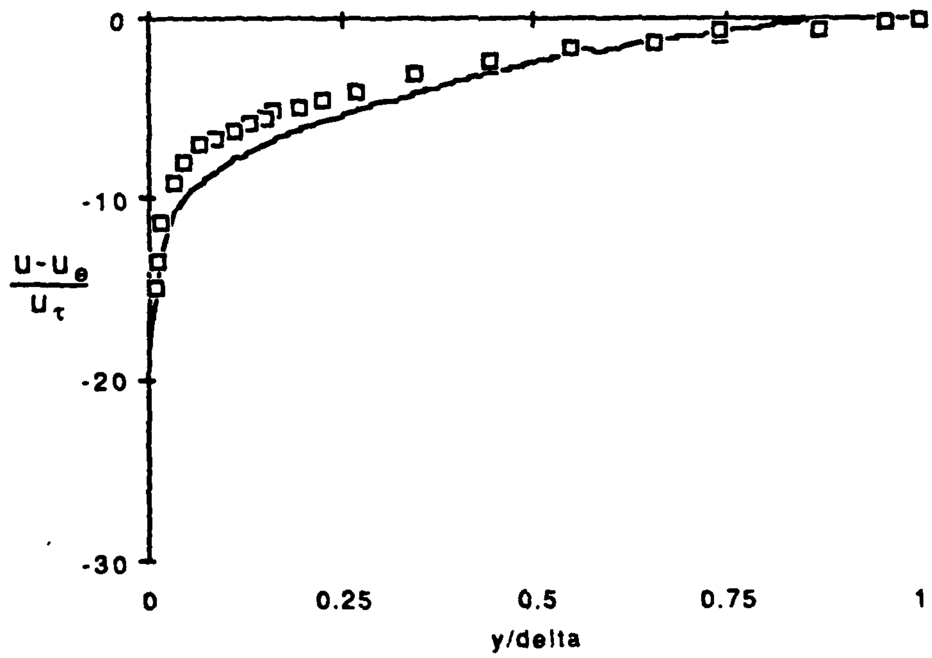


Fig. 6 Velocity-defect Profile in Incompressible Coordinates.

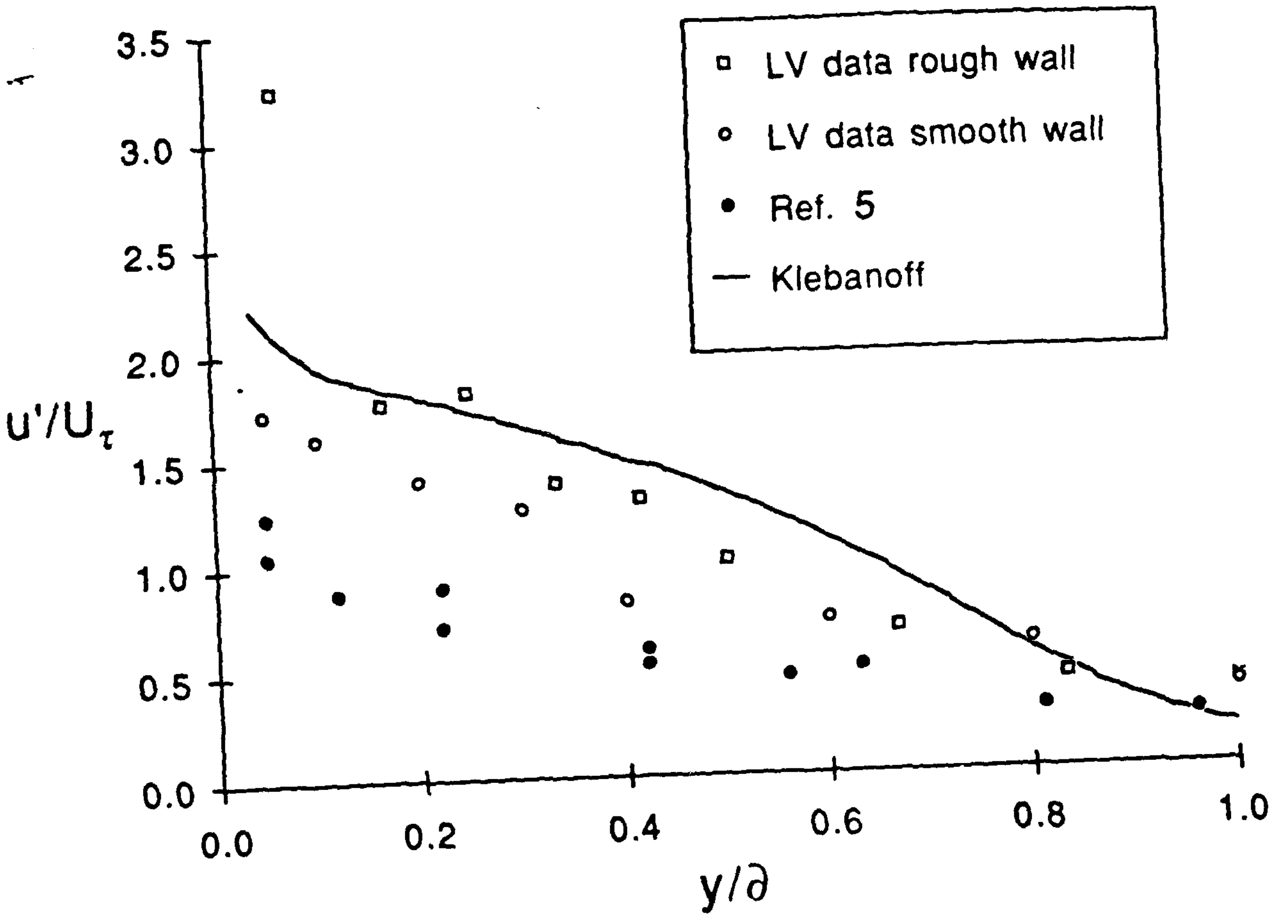


Fig. 7 Wall Turbulence Measurements.

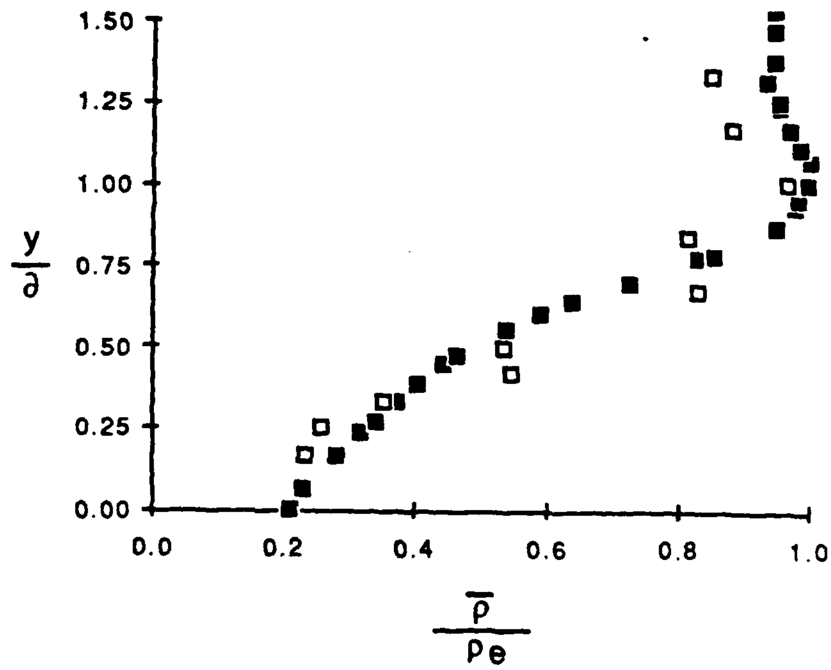


Fig. 8 Mean Density Profiles.

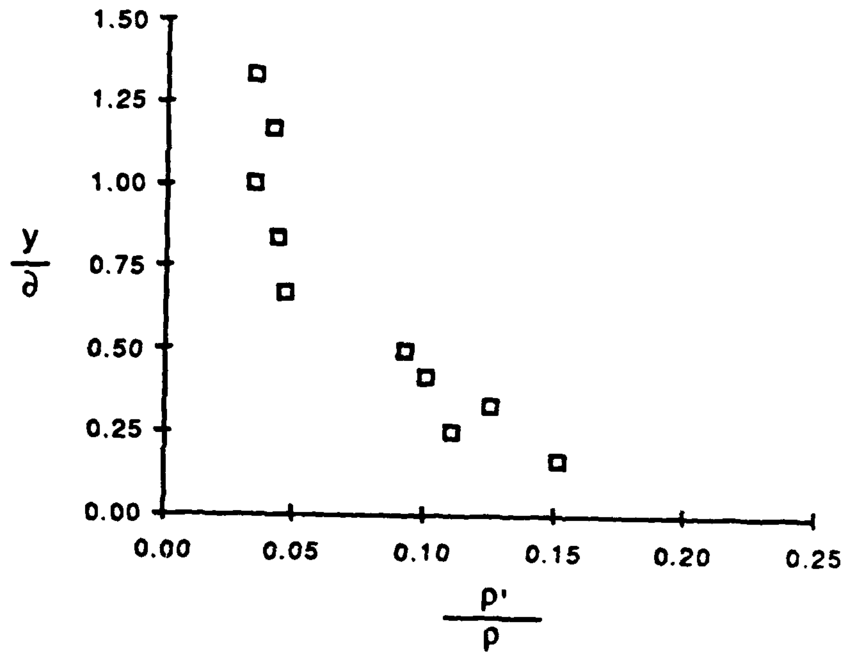


Fig. 9 Density Fluctuation Levels.

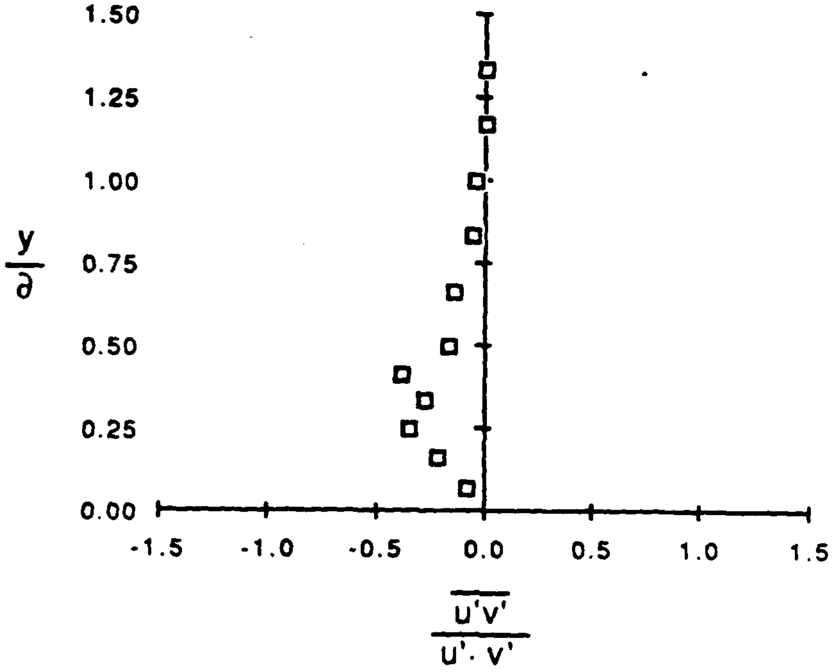


Fig. 10 Turbulent Velocity Cross-Correlation Coefficient.

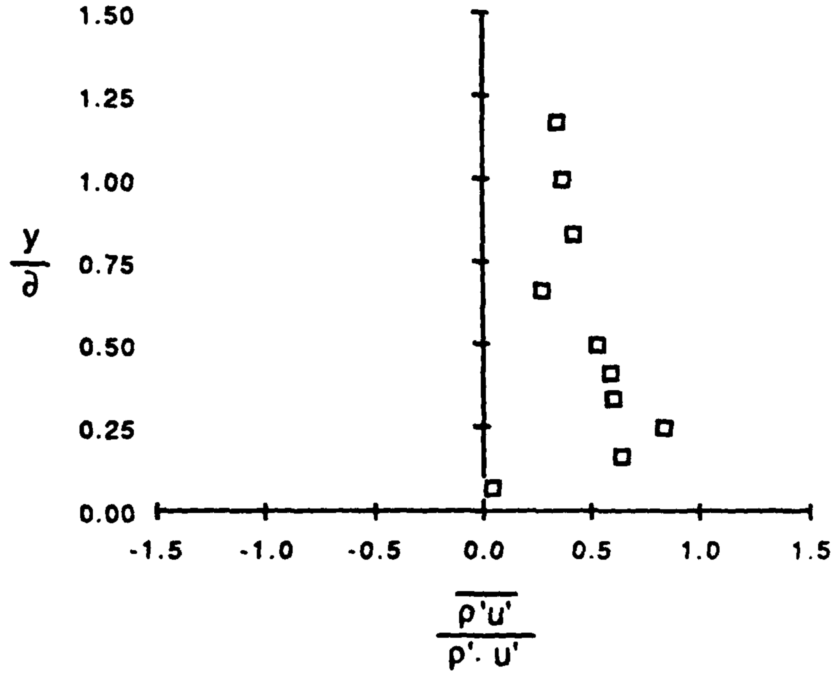


Fig. 11 Density-Velocity Cross-Correlation Coefficient.

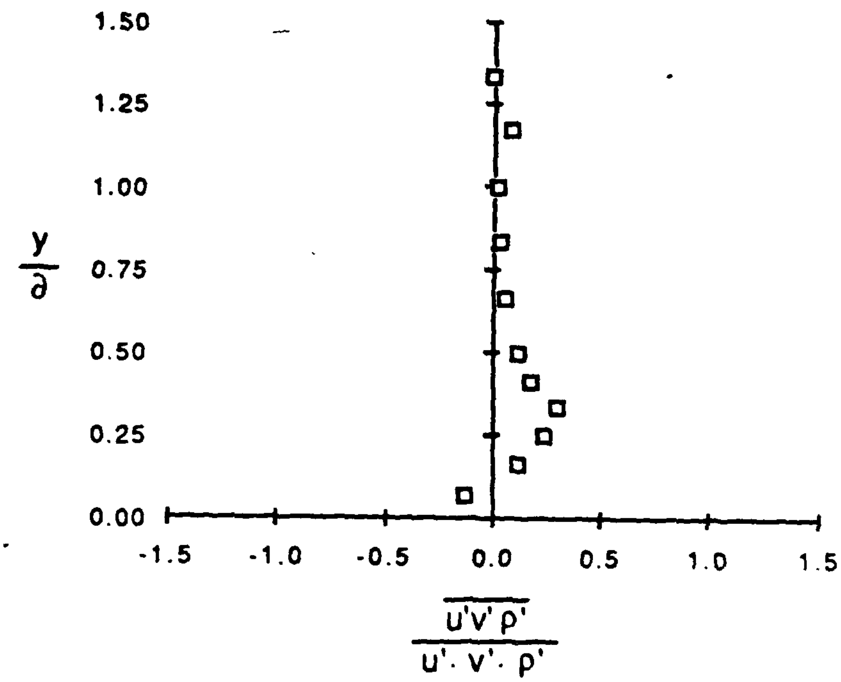


Fig. 12 Density-Velocity Triple Correlation.

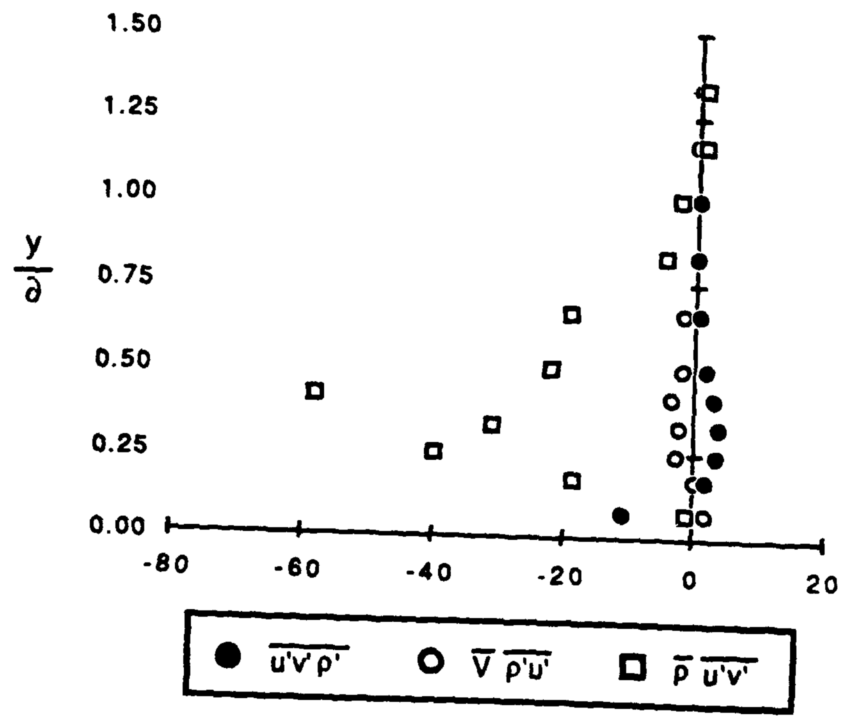


Fig. 13 Compressible Shear Stress Distribution.